Department of the Navy
Bureau of Ordnance
Contract NOrd-16200
Task 1

WATER TUNNEL INVESTIGATION OF TWO-DIMENSIONAL CAVITIES

R. L. Waid

Hydrodynamics Laboratory
California Institute of Technology
Pasadena, California

Report No. E-73.6 September 1957

ABSTRACT

The results of drag measurements on a flat lamina, wedges, a circular cylinder and a scoop channel in two-dimensional cavitating flow in the High Speed Water Tunnel are presented. Cavity geometry data are also included. The results are compared with available theoretical drag coefficients and cavity dimensions.

INTRODUCTION

Theoretical calculations of full cavity flow about symmetric two-dimensional bodies have been performed by a number of investigators. These analyses have considered full cavity flow in an infinite free stream[1-4*], as well as the effects of fixed tunnel walls[5-7] or a free jet[8] upon the drag and shape of the cavity. This report presents the results of an experimental investigation which was conducted in the High Speed Water Tunnel[9] to obtain the drag coefficients and characteristic cavity dimensions of six two-dimensional bodies as a function of cavitation number. The two-dimensional working section[10] in which the tests were conducted has fixed walls so that the results presented here are for the particular case of cavity flow with wall effects. Various theoretical results are included with the experimental data for comparison.

EXPERIMENTAL PROCEDURE

The two-dimensional models tested were a scoop channel, flat plate, 45, 15 and 5-degree half-angle wedges and a right circular cylinder, Fig. 1. The models were installed in a horizontal plane spanning the 2.90-in. wide two-dimensional test section. The centerline of the models was midway between the floor and the ceiling of the 14-in. high test section. Table I gives the actual model dimensions and the ratios of model height-to-tunnel height and model chord-to-tunnel height.

The installation of the model on the external three-component balance[11] in the two-dimensional working section was by the method described by Kermeen in Ref. 10.

The test procedure was to operate the tunnel at a constant upstream velocity and to vary the tunnel static pressure to obtain data over a wide range of partially and fully cavitating flow. This process was repeated at several velocities from 25 to 40 fps for each model.

Drag force, cavity pressure, tunnel static pressure, velocity head, and profile photographs of the cavity were the recorded experimental data.

---

*Superscripts denote references in the bibliography.

The cavity pressure was measured by a probe which extended from the tunnel sidewall into the cavity-filled wake of the model.

EXPERIMENTAL RESULTS

The recorded drag force data were corrected for the tare effects of the base plate mounting, and the corrected drag data were reduced to dimensionless drag coefficients as defined in the list of symbols, Table II. The pressure data were reduced to obtain the cavitation numbers for each set of test conditions. In all cases the cavitation number was based on the actual measured cavity pressure. Projected images of the cavity photographs were measured to obtain the dimensionless characteristic lengths and widths of the cavities.

Figure 2 presents the drag coefficient data for the six models as a function of the cavitation number. The solid symbols represent data obtained with partially cavitating flow where the cavity was filled with a rapidly moving combination of gas-filled bubbles and water, Fig. 3. The open symbols denote data obtained with a full cavity, which was a single steady attached cavity, Fig. 4. Theoretical drag coefficients for the infinite stream condition computed by Perry[2] using the theory of Plesset and Shaffer are included for comparison. The theoretical data do not include the effects of viscous drag. The experimental drag coefficients for full cavity flow are within several percent of the theoretical results by Perry[2] for which calculations are available.

Figures 5 and 6 present the maximum cavity width and the cavity length as functions of the cavitation number for the six models. The limited length of the viewing window made it impossible to measure the characteristic dimensions of the longer cavities, so these points are indicated by arrows. Infinite stream theoretical results by Perry and Tulin are included, as well as some calculations by Cohen and Gilbert who consider the effects of the finite width of the tunnel walls using the linearized theory. The latter calculations for the 15-degree half-angle wedge were based on a chord-to-tunnel width ratio of 0.050. The obvious differences between the observed cavity dimensions and the theoretical infinite stream results by Perry and Tulin are primarily due to the finite extent of the tunnel. This is indicated by the fair agreement between the observed cavity width and those indicated by Cohen and Gilbert. It should be noted (Fig. 5) that for the 15-degree half-angle wedge the cavity widths in an infinite stream, as computed after Tulin, are in close agreement with those computed by Perry after Plesset and Shaffer. This suggests that the approximations employed in the linearized theory of Tulin are reasonably valid for determining the cavity widths for small angle wedges.

The experimental cavity lengths prescribed in Fig. 6 are defined as twice the axial distance from the point of flow separation to the maximum width of the cavity. The results of the Plesset and Shaffer theory have been applied to this definition of cavity length. Unfortunately, the linearized cavity lengths cannot be modified to this definition. However, the Cohen and Gilbert results have been included along with Tulin's results to suggest the order of magnitude of the wall effects on the cavity length. It appears that if the results of Perry (Fig. 6) were modified for wall effects, as suggested by the linearized theories, the comparison between experimental and theoretical cavity lengths would be very similar to the comparison for cavity widths as shown in Fig. 5.

TABLE I

	Name	Model			Ratio	
		Half Angle (Degrees)	Height (Inches)	Chord (Inches)	Model Height / Tunnel Height	Model Chord / Tunnel Height
a	Scoop channel	180	0.371	0.125	.027	-
b	Flat plate	90	0.375	-	.027	-
c	Wedge	45	0.375	0.188	.027	.013
d	Wedge	15	0.371	0.693	.027	.050
e	Wedge	5	0.304	1.747	.022	.125
f	Right circular cylinder		0.375	0.375	.027	.027

TABLE II

LIST OF SYMBOLS

A	=	Frontal area of body = d x span
D	=	Drag force on body
d	=	Width of body at point of cavity formation
d_m	=	Maximum width of cavity
ℓ	=	Length of cavity = 2 x distance from point of cavity formation to maximum width of cavity.
P_k	=	Pressure in cavity
P_o	=	Static pressure in free stream
ρ	=	Density of free stream
V	=	Velocity of free stream
σ	=	Cavitation number = $\dfrac{P_o - P_k}{\rho/2\, V^2}$
C_D	=	Drag coefficient = $\dfrac{D}{\rho/2\, V^2 A}$
dm/d	=	Characteristic cavity width
ℓ/d	=	Characteristic cavity length

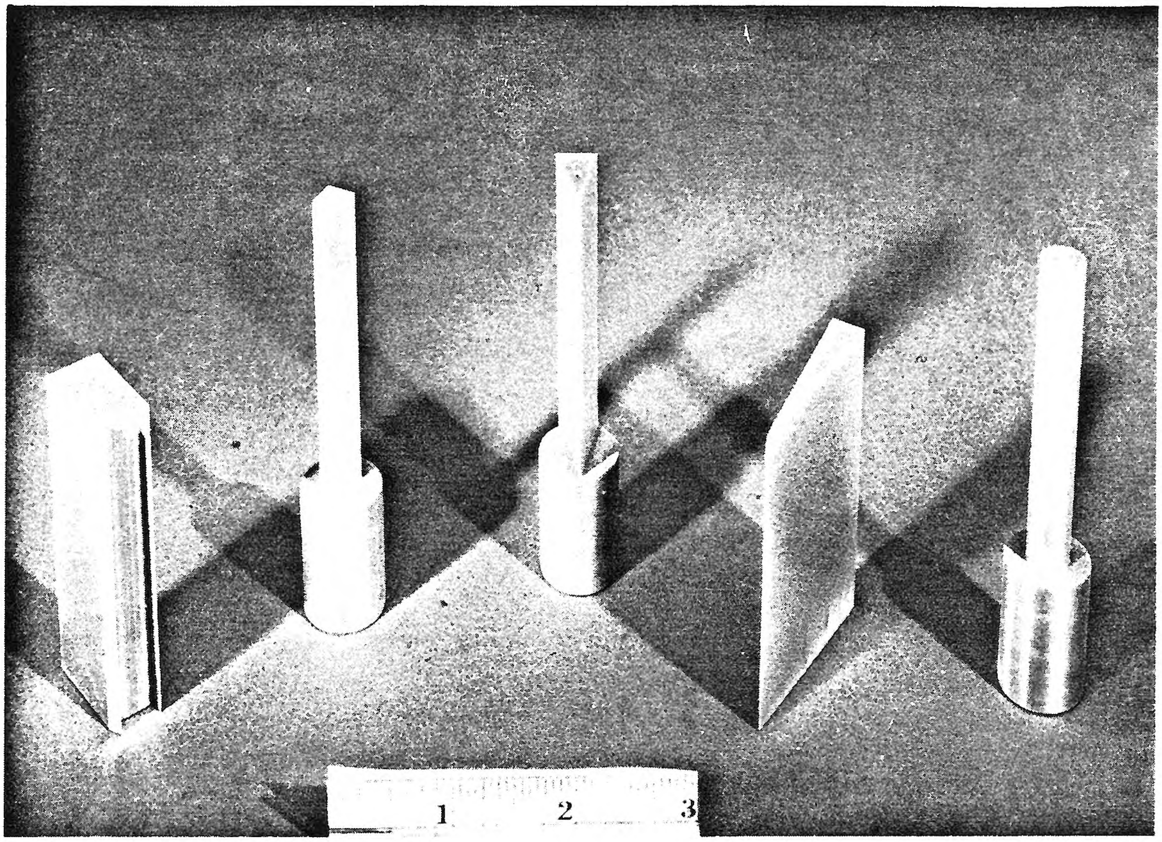

Fig. 1. Two-dimensional models.

a. Scoop channel
b. Flat plate
c. 45-degree wedge
d. 15-degree wedge
e. 5-degree wedge
f. Right circular cylinder

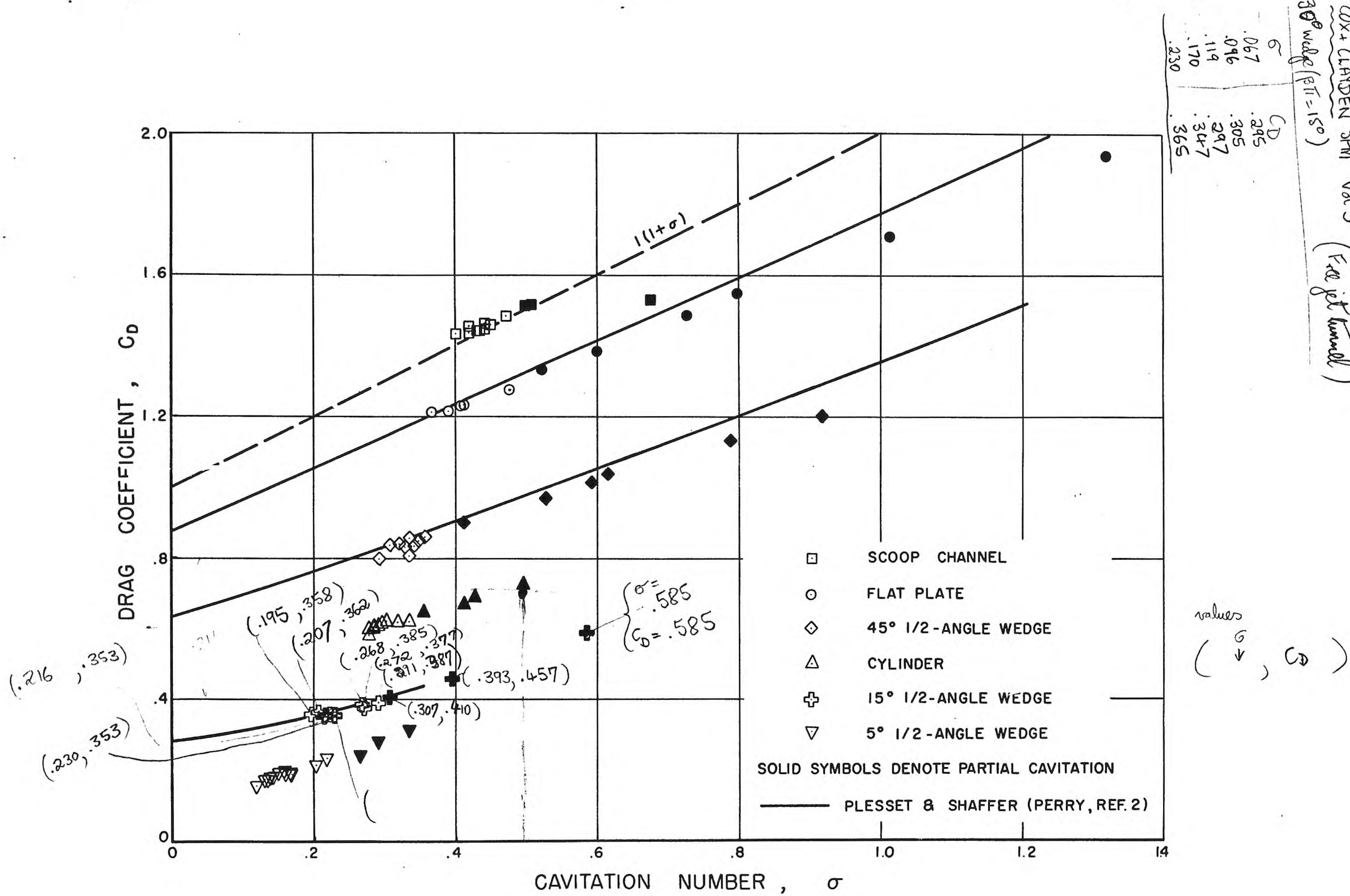

Fig. 2. Drag coefficient as a function of cavitation number.

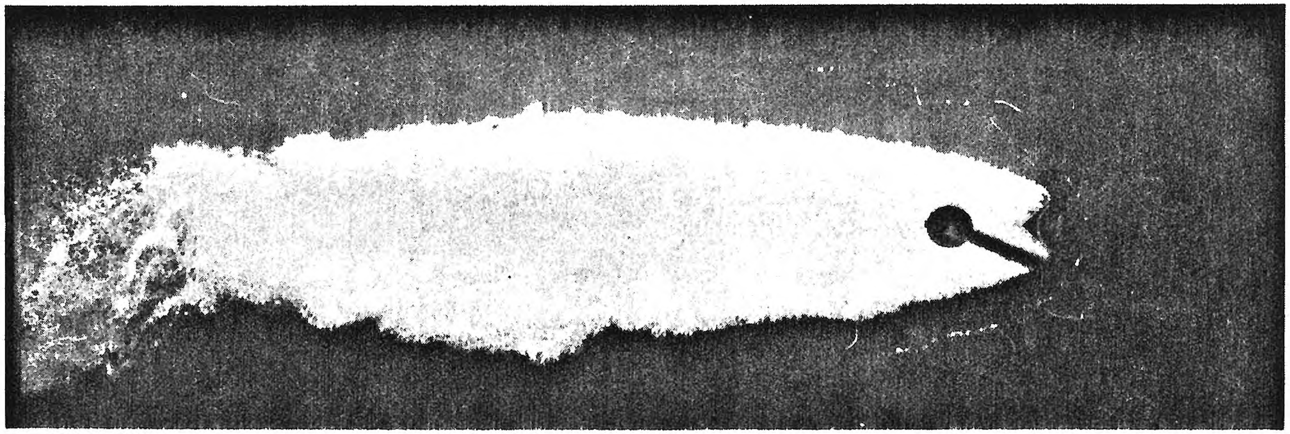

Fig. 3. Gas bubbles and water-filled cavity in partially cavitating flow behind flat plate.

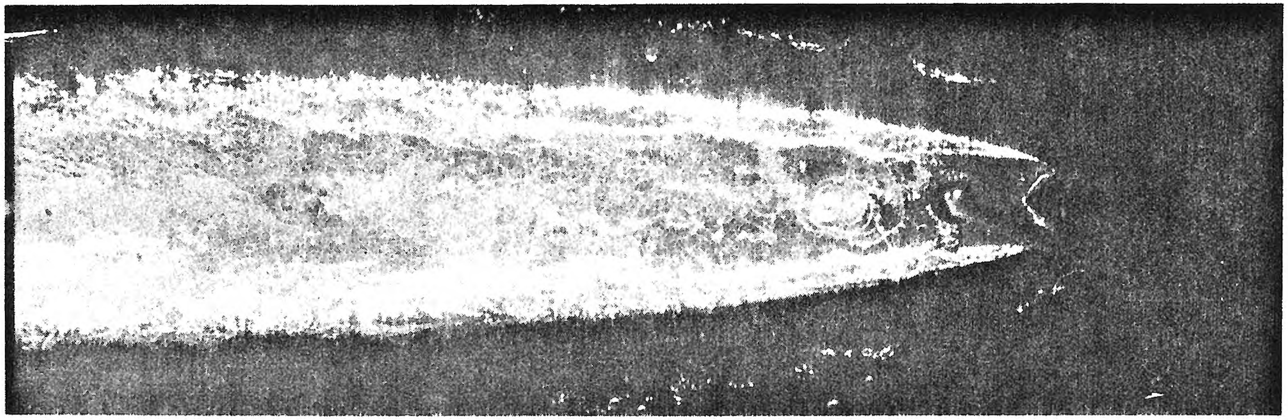

Fig. 4. Steady attached cavity in full cavity flow behind flat plate.

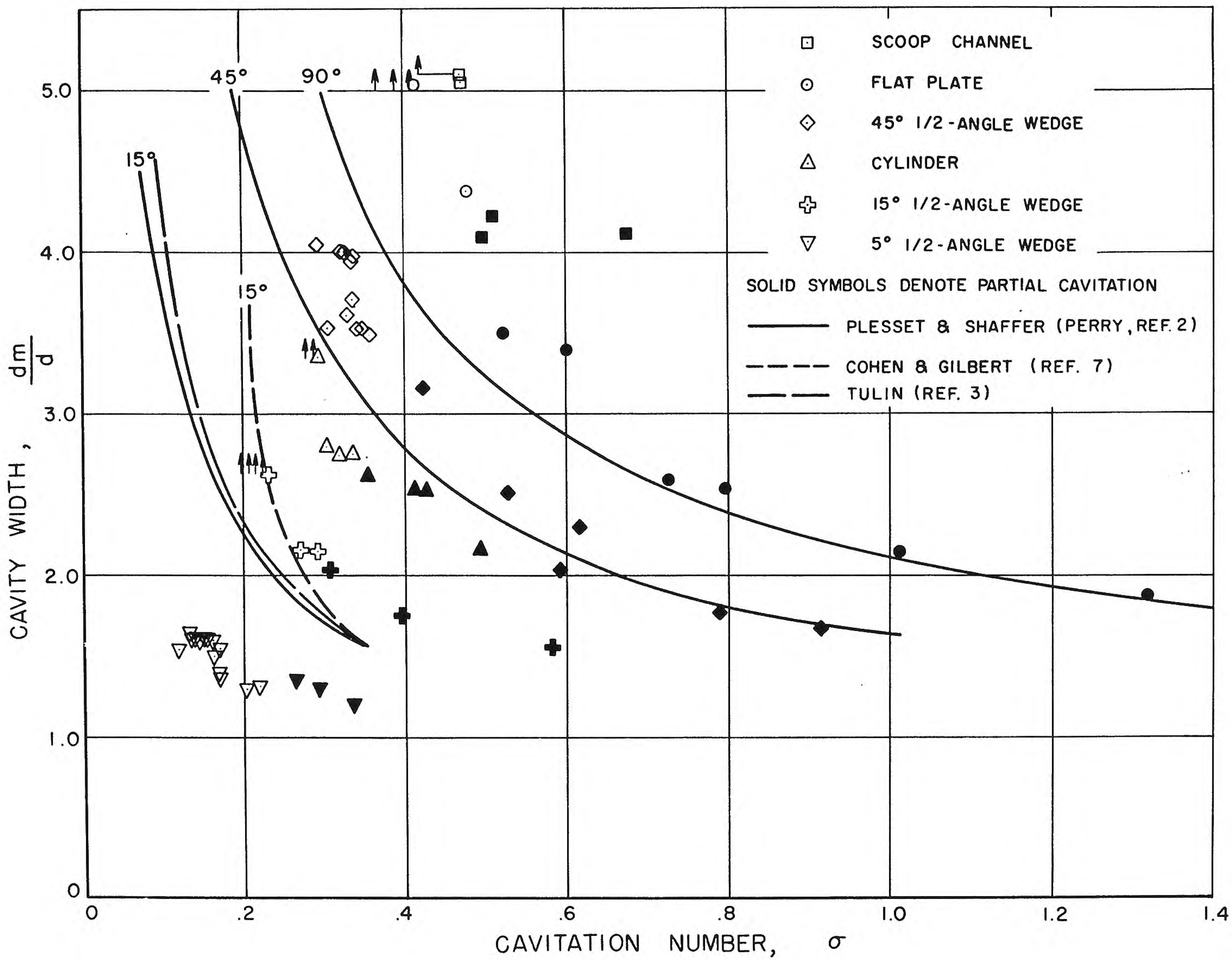

Fig. 5. Cavity width as a function of cavitation number.

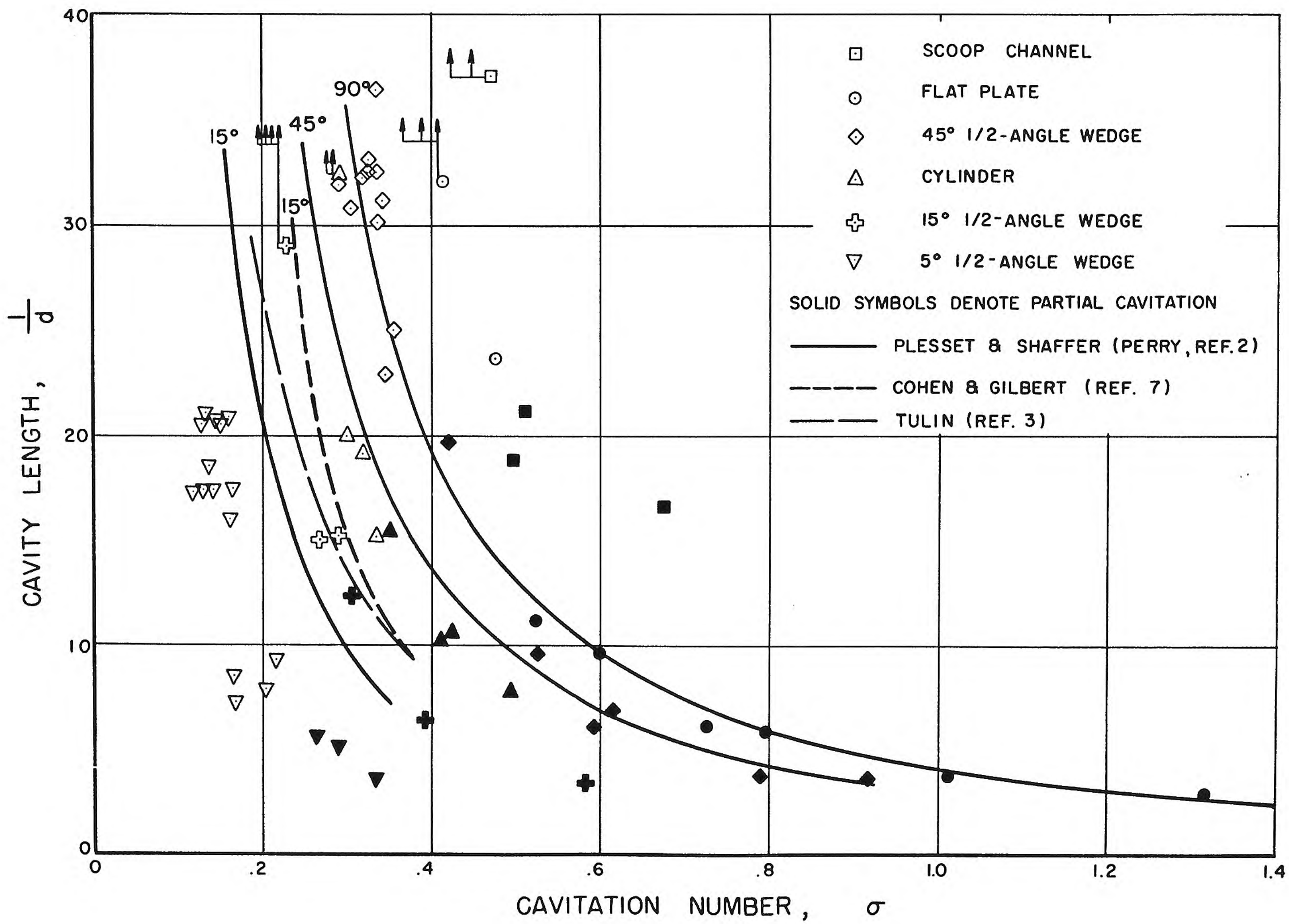

Fig. 6. Cavity length as a function of cavitation number.

BIBLIOGRAPHY

1. Plesset, M. S., and Shaffer, P. A., Jr.,"Cavity Drag in Two and Three Dimensions", U. S. Naval Ordnance Test Station, NAVORD Report 1014, October 1949.

2. Perry, Byrne, "Evaluation of the Integrals Occurring in the Cavity Theory of Plesset and Shaffer", California Institute of Technology, Hydrodynamics Laboratory Report No. 21-11, Dec. 1952.

3. Tulin, M. P., "Steady Two-Dimensional Cavity Flows about Slender Bodies", David Taylor Model Basin Report No. 834, May 1953.

4. Wu, T. Yao-tsu, "A Free Streamline Theory for Two-Dimensional Fully Cavitated Hydrofoils", California Institute of Technology, Hydrodynamics Laboratory Report No. 21-17, July 1955

5. Birkhoff, G., Plesset, M. S., and Simmons, N., "Wall Effects in Cavity Flow", Part I, Quarterly of Appl. Math., Vol. VIII, No. 2, p. 413, January 1952.

6. Armstrong, A., and Tadman, K., "Wall Corrections to Axially Symmetric Cavities in Circular Tunnels and Jets", Armament Research Establishment Report No. 7/52, March 1953.

7. Cohen, H., Gilbert, R., "Two-Dimensional, Steady Cavity Flow about Slender Bodies in Channels of Finite Breadth", Rensselaer Polytechnic Institute, Dept. of Mathematics, RPI Math. Report No. 3, Sept. 15, 1956.

8. Cohen, H., Tu, Yih-O, "A Comparison of Wall Effects on Supercavitating Flows Past Symmetric Bodies in Solid Wall Channels and Jets", Rensselaer Polytechnic Institute, Dept. of Mathematics, RPI Math. Report No. 5, Oct. 1, 1956.

9. Knapp, R. T., Levy, J., O'Neill, J. P., and Brown, F. B., "The Hydrodynamics Laboratory of the California Institute of Technology", Trans. ASME, July 1948.

10. Kermeen, R. W., "Water Tunnel Tests of NACA 4412 and Walchner Profile of Hydrofoils in Noncavitating and Cavitating Flows", California Institute of Technology, Hydrodynamics Laboratory Report No. 47-5, January 1956.

11. Hotz, G. M., and McGraw, J. T., "The High Speed Water Tunnel Three-Component Force Balance", California Institute of Technology, Hydrodynamics Laboratory Report No. 47-2, December 1954.

DISTRIBUTION LIST

Copy No.	
1-4	Chief, Bureau of Ordnance, Navy Dept., Washington 25, D. C. Attn: Code ReO-3
5-8	Chief, Bureau of Ordnance, Navy Dept., Washington 25, D. C. Attn: Code ReU
9-10	Chief, Bureau of Ordnance, Navy Dept., Washington 25, D. C. Attn: Code Ad3
11-13	Chief, Bureau of Aeronautics, Navy Dept., Washington 25, D. C.
14-18	Chief, Bureau of Ships, Navy Dept., Washington 25, D. C.
19-21	Chief, Office of Naval Research, Navy Dept., Washington 25, D. C. Attn: Code 438
22	Commanding Officer, Office of Naval Research Branch Office, 1030 East Green Street, Pasadena 1, California
23-24	Commanding Officer and Director, David Taylor Model Basin, Washington 7, D. C.
25-26	Commanding Officer, U. S. Naval Underwater Ordnance Station, Newport, Rhode Island
27-28	Commander, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland
29-30	Commander, U. S. Naval Ordnance Test Station, Pasadena, California
31	Commander, U. S. Naval Ordnance Test Station, China Lake, California
32	Director, Experimental Towing Tank, Stevens Institute of Technology, via: Bureau of Aeronautics Representative c/o Bendix Aviation Corp., Eclipse-Pioneer Division, Teterboro, New Jersey
33	Director, Ordnance Research Laboratory, Pennsylvania State University, University Park, Pennsylvania
34	Alden Hydraulic Laboratory, Worcester Polytechnic Institute, Worcester, Mass., via: Inspector of Naval Material, 495 Summer Street, Boston 10, Mass.
35-36	Librarian, U. S. Naval Postgraduate School, Monterey, Calif.

DISTRIBUTION LIST (cont'd)

Copy No.	
37-46	British Joint Services Mission, Navy Staff, via: Chief, Bureau of Ordnance, Navy Dept., Washington 25, D. C., Attn: Code Ad8
47-49	Commander, U. S. Naval Proving Ground, Dahlgren, Virginia
50-51	National Advisory Committee for Aeronautics, Langley Memorial Aeronautical Laboratory, Langley Field, Virginia
52	National Advisory Committee for Aeronautics, Lewis Flight Propulsion Lab., Cleveland Airport, Cleveland, Ohio
53	Director, National Advisory Committee for Aeronautics, 1512 H Street, N. W., Washington 25, D. C.
54	Director, National Advisory Committee for Aeronautics, Ames Laboratory, Moffett Field, California
55-56	Commander, Air Research and Development Command, Post Office Box 1395, Baltimore 3, Maryland
57	ASTIA Reference Center, Technical Information Division, Library of Congress, Washington 25, D. C.
58-63	Director, Armed Services Technical Information Agency, Documents Service Center, Knott Building, Dayton 2, Ohio. Attn: DSC-SA